Studies of Mine Burial in Coastal Environments
Ripple Dynamics and Benthic Transformations under Variable Wave Forcing

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LONG-TERM GOALS

The long-term goal of our research program is to improve scientific knowledge relevant to the understanding and modeling of fluid dynamic and sedimentary processes of oceanic coastal zone, with the aim of contributing to the mine countermeasures (MCM) activities of the US Navy. Of particular interest is the creation of scientific knowledge relevant to the parameterization of coastal hydrodynamic processes that will help develop predictive modeling capabilities and doctrine algorithms. The first project concerns the burial of mines in the shoaling zone under different background flow and sediment conditions whereas the focus of the second project is on benthic ripple formation and evolution. In all, the response of fluid-sediment and fluid-sediment-mine interfaces and two-phase sediment-water flow in the benthic boundary layer to changing (evolving) far-field wave forcing is the central theme of our research work.

OBJECTIVES

The scientific objectives of our current research are to: (i) study the evolution of an initially flat sandy beach under nonlinear progressive waves; (ii) investigate the long-term evolution of bottom topography in relation to mine burial scenarios; (iii) document the behavior of model mines in the shoaling zone; and (iv) study the bottom morphology under variable (non-stationary) wave forcing. Particular attention was given to: (i) the water motion and ensuing scour around cylindrical mines placed on a sandy slope under progressive nonlinear waves; (ii) morphodynamics of sand beds under stationary water waves; (iii) morphodynamics of sand ripples under non-stationary water waves; (iv) periodic or permanent burial of mines; and (iv) velocity fields around low-aspect ratio cylinders on a flat bottom under steady and oscillatory flows.

APPROACH

Comprehensive laboratory experimental and numerical research programs were conducted to investigate scour around and burial of cylindrical mines and the dynamics of sand ripples under changing wave conditions. The research completed consists of three main components. Firstly, to

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measure, in large-scale tank experiments the salient parameters pertinent to the scour/burial of mines and the spatial variability of ripple fields under shoaling nonlinear progressive waves that mimic coastal waters. Secondly, to understand and model the response of ripple morphology to predetermined changes in wave forcing. Thirdly, to extrapolate laboratory measurements to oceanic conditions to help interpret field measurements (SAX99 and SAX04). The major emphasis was on improving the physical understanding and parameterizations of flow, sediment transport and scouring processes around mines and associated ripple processes. The results are to be included in the probabilistic (expert systems) model that is being developed as the end product of MBP.

WORK COMPLETED

Our previous studies dealt with the behavior of disk-shaped, spherical and cylindrical model mines on horizontal and slopping beaches under different flow conditions [1-6]. The main outcomes of these scaled experimental studies are new semi-empirical models and parameterizations of varying complexity that describe mine behavior and bottom morphodynamics under different wave, slope and mine conditions typical of the coastal zone. The most-recent results [7-9] include the development of a scour/burial regime diagram and parameterizations for ripple transitional processes at steady wave forcing. The above research is being extended to include (i) ripple dynamics and benthic transformations under variable wave forcing, and (ii) 3D flow structure around short horizontal cylinders in steady and oscillatory flows. A large wave tank that can generate progressive shoaling waves along a sandy slope and a towing tank with steady and periodic flow capabilities (both located at ASU) are the principle experimental apparatuses. Quantitative data are obtained using high-resolution video cameras, three-component acoustic Doppler velocimetry (ADV), "structural" light technique and other modern fluid dynamics methods including stereoscopic particle image velocimetry (PIV).

RESULTS

Our recent findings are presented in detail in [7-11], and their summary is as follows: (*i*) A scour/burial regime diagram for cylindrical mines as a function of the Keulegan-Carpenter number, KC, and Shields parameter, Sh, was developed; (*ii*) Semi-empirical formulae for the calculation of scour depth as a function of time, the equilibrium maximum scour depth and conditions of mine burial were proposed; (*iii*) Experimental data on ripples formation, instabilities and drift under steady wave forcing were collected and explained; (*iv*) Data on ripple dynamics and related transitional processes under variable wave forcing were collected and explained; (*v*) A dynamical description for the 3D flow structure around short horizontal bottom cylinder was proposed and verified experimentally.

Our latest results [10] show the importance of intense horseshoe vortices (see schematic in Fig.1), which are generated periodically in the lee side of a short bottom cylinder in steady and oscillatory flows. These experiments were conducted using a long towing tank under both steady and oscillatory flow conditions. In the range of parameters studied (Reynolds number Re = 270-4500, KC = 4-28), the near field is found to be dominated by large horseshoe vortices of sizes comparable to the size of the cylinder. The detailed topological structure and characteristics of these vortices are important in understanding and correctly parameterizing large scour observed around cylindrical mines on sandy beds (see, e.g., Fig. 8 in [7]). A simplified model consisting of a system of energetic “horseshoe” vortices was proposed to explain the observations. For the range of parameters used in the experiments, horseshoe vortices form periodically around the cylinder under steady or oscillatory flows. In the steady flow case, these vortices have the same sign of rotation and are advected periodically away from the cylinder (Fig. 2). The dimensionless shedding frequency, the Strouhal number, first slowly decreases with increasing Re and then remains approximately constant. The horseshoe vortices are rather energetic and their normalized intensity (circulation) is proportional to Re. Away from the cylinder, the limbs of the horseshoe vortex approach each other forming a narrow neck while the head of the vortex deflected upward away from the bottom boundary. The narrow neck can be broken and reconnected forming a vortex ring-like structure, which may self propagate and advect downstream. The other reconnected parts (legs) provide roots for the synthesis of the succeeding vortex. In oscillatory flow, horseshoe vortices of opposite sign are formed periodically on both sides of the cylinder (Fig. 1). In the range of parameters studied, two vortices of the same sign were observed at each side of the cylinder during each half of the oscillation cycle. One of them has been flipped from one side of the cylinder to the other with the change of the flow direction and the other is a new vortex generated during the half cycle in point. The two vortices (of the opposite sign) form a pair-like structure in cross section, while shedding away from the cylinder periodically.

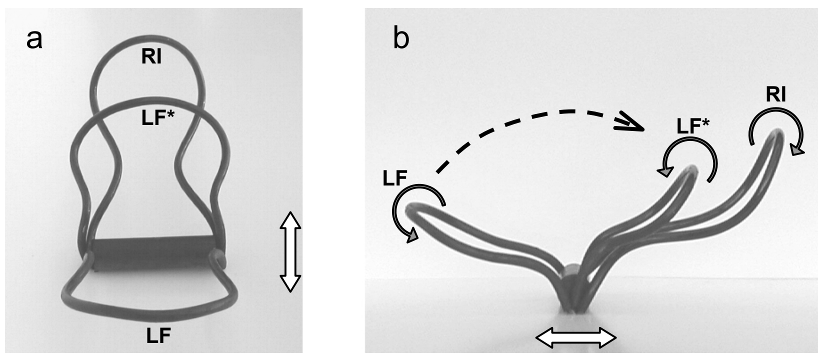

Fig. 1. Top view (a) and side view (b) schematics showing the process of horseshoe vortex flipping from one side of the cylinder to another in oscillatory flow. When flow moves from right to left a vortex (LF) is generated on the left side of the cylinder in (b). When the flow changes its direction a vortex (RI) is generating at the right side of the cylinder; at the same time the vortex (LF) flips over the cylinder [dashed line in (b) shows the trajectory of its advection] and takes a position (LF*) near the vortex (RI). The vortices (LF*) and (RI) have opposite signs of rotation, and in the vertical plane of observation they are seen as a "vortex pair".

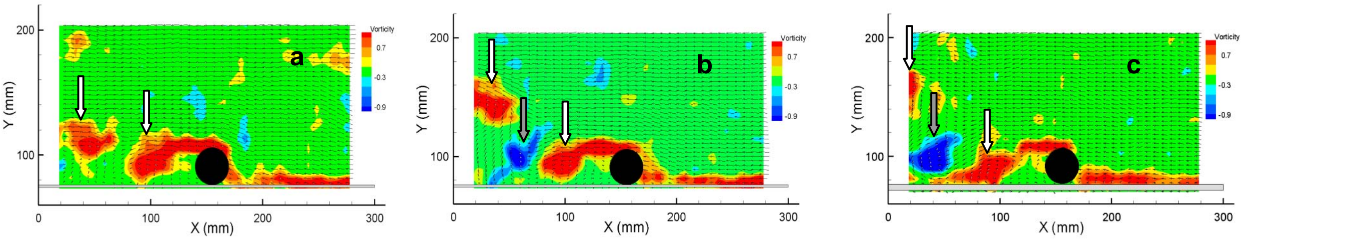

Fig. 2. Side-view PIV data showing the cross section of two horseshoe vortices (a) and the reconnected vortex ring-like structure (b, c). The flow direction is from right to left. Velocity vectors are superposed on the vorticity field shown by red (positive) to blue (negative). Experimental parameters: U = 2 cm s^{-1}, D = 3 cm, Re = 600, and the time interval between the images is ~1.3 s.

Experiments on the dynamics of sand ripples under variable wave forcing were conducted using the large wave tank with progressive shoaling waves along the sandy slope. Waves with relatively small (S), moderate (M) and large (L) intensities (as specified by the wave paddle excursion, ε, and frequency, ω) were used to realize three basic cases of cyclic variation of wave forcing, namely (i) L-M-L, (ii) M-L-M, and (iii) L-S-L. Upon the change of forcing, the ripples adjusted themselves to the new wave forcing through different adjustment processes. Depending on the forcing transitions (L-M, M-L or L-S), three basic ripple adjustment processes were documented as: (i) ripple splitting, (ii) ripple re-growth and (iii) ripple flattening [11].

Ripple splitting and re-growth were observed (see example in Fig. 3) during large to moderate wave forcing transition (L-M). In this process, rather than simply transitioning from larger to smaller size, the ripples first split into two nominally identical smaller ripples, which then grow towards their new equilibrium size (re-growth).

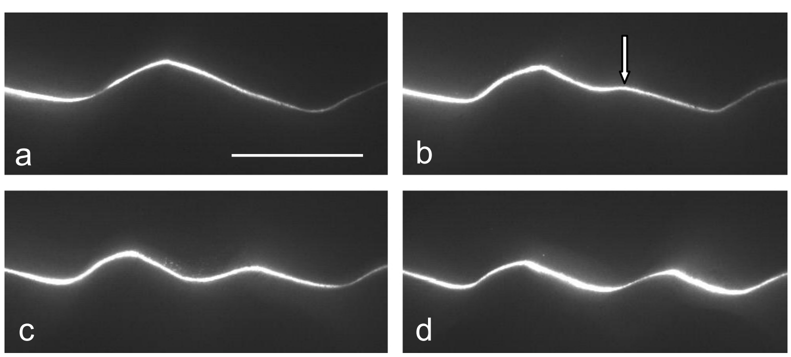

Figure 3. Sequence of ripple profiles showing the ripple splitting. After wave forcing was changed from (L) to (M), an initially large ripple (a) becomes unstable and a disturbance (shown by an arrow) arises on initially smooth ripple profile (b). With time this disturbance grows (c) forming a new ripple. As a result the number of ripples doubles and ripple size decreases in half (d). The length scale (10 cm) is given by horizontal line in (a).

Similarly, during moderate to large wave forcing transition (M-L), ripple re-growth was observed as the main adjustment process that transforms smaller ripples to the larger ones. Finally, when large to small forcing transition (L-S) was reproduced, crests of the ripples, which were formed under forcing (L), were flattened and the ripple length increased slightly. The results of observations were explained by extending a phenomenological model proposed earlier in [8] to interpret experimental results on the generation of ripples on an initially flat bed under steady wave forcing. The latter model showed that a ripple system relaxes with time to a new state, after initiation of wave forcing (a strong disturbance), according to the general dependence

$$A = A_0[1 - \exp(-t/t^*)],$$

where A is a characteristic variable, A_0 its steady value, t the elapsed time upon initiating the change and t^* a characteristic relaxation time. This rather intriguing (universal?) similarity behavior was observed (notwithstanding the strong nonlinearity of the system) for the ripple front position along the slope as well as for the ripple wavelength/height and score depth around model mines [7-10].

In [11], the above dependence was employed to describe ripples under changing wave forcing. A comparison between the measured ripple characteristics (ripple length, L, and height, h) at different times for the case of cyclic variation of wave forcing L-M-L and the model predictions is given in Fig. 4. Experimental data on ripple characteristics (length and height) as a function of time are shown by symbols and the model predictions are shown by solid lines. As can be seen the model correctly describes this rather complicated process of ripple adjustment under changing wave forcing. Similar results were obtained for M-L-M, and L-S-L cyclic variation of wave forcing [11].

Recognizing the importance of ripple profiles on the intensity of acoustic backscatter from ocean bottom sediments, which is often employed to detect buried objects (mines), detailed ripple-profile measurements were taken in a series of experiments conducted under different flow conditions. Our preliminary results [12] show that under shoaling progressive waves a "universal" similarity ripple profile (Fig. 5) may be obtained with h and L as normalizing variables.

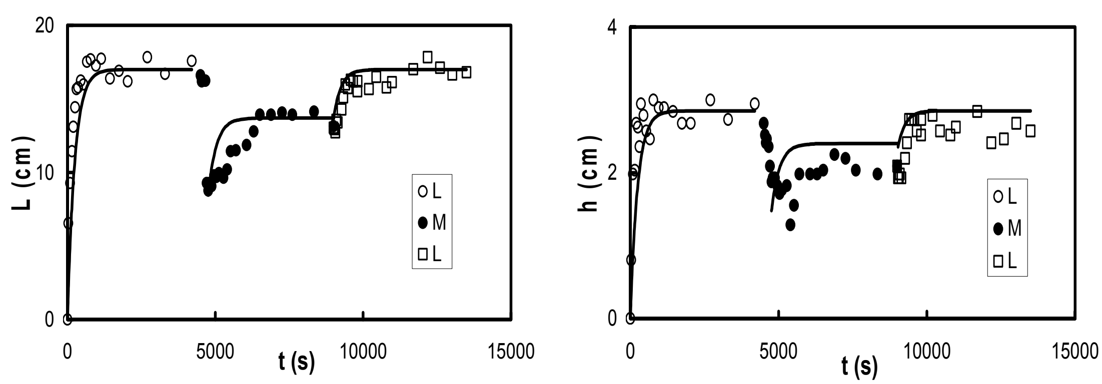

Figure 4. Ripple length, L (left), and ripple height, h (right), adjustment with time, t, at a particular location of the experimental run L-M-L. Symbols – measurements; solid lines – predictions based on the model proposed.

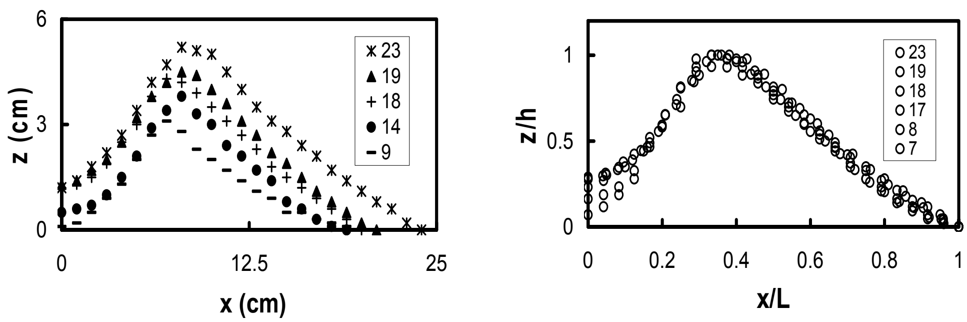

Figure 5. Left - dimensional data on equilibrium ripple profiles in different sections in the wave tank (see legend). Right – nondimensional "universal" ripple profiles obtained in all sections. Experimental conditions: $\varepsilon = 25$ cm, $\omega = 0.4$ Hz.

IMPACT/APPLICATIONS

The scour around and the burial of large cylindrical objects, such as ship mines, on a sandy sloping bottom submerged in the wave boundary layer typical of a coastal zone and associated ripple dynamics are not well understood from a fundamental point of view. This project has made fundamental advances in this regard by utilizing integrated laboratory and theoretical/numerical approaches.

TRANSITIONS

The importance of field measurements cannot be over emphasized in developing mine burial predictive capabilities. We are interacting with the field experimental groups from the University of South Florida and Woods Hole Oceanographic Institution in comparing their MBP field measurements with predictions based on laboratory results. The agreement thus far is encouraging. Close-collaboration is maintained with SAX99 and SAX04 field groups, and attempts will be made to place the results of field and laboratory programs in the contexts of each other. The new parameterizations so far developed on scour around mines were provided to the Johns Hopkins Applied Physics Laboratory Group (Drs. Alan Brandt and Sarah Rene) to be incorporated into the mine burial experts system.

RELATED PROJECTS

An attempt was made to compare the experimental results on scour rates, burial and flow regimes with those predicted by operational mine burial models: WISSP, NBURY and DRAMBUI. We have already started collaboration with Carl Friedrich (College of William and Mary) who is familiar with the details of these models. Also, the cases with scour are being compared with the predictions of the Inman/Jenkins research model. We are continuing our collaboration with Stephan Grilli (University of Rhode Island) and Chiang Mei (MIT).

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